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METEOROLOGICAL OFFICE

GEOPHYSICAL MEMOIRS No. 69

(Twelfth Number, Volume VII)

RAINFALL AT FRONTS OF DEPRESSIONS

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Published by the Authority of the Meteorological Committee

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LONDON

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RAINFALL AT FRONTS OF DEPRESSIONS

§ 1—INTRODUCTION

A few years ago, in a paper dealing with the rainfall of the years 1922–4 at Aberdeen, Eskdalemuir and Kew Observatories, the writer (1)* found that the rainfalls occurring at warm fronts and cold fronts had characteristic semi-diurnal variations of very considerable amplitude. The variations in neither case were symmetrically semi-diurnal, there being also diurnal effects causing the principal maximum of warm front rain to occur in the early morning hours and the principal maximum of cold front rain to occur in the afternoon. If the two types of rainfall were averaged up the times of maxima corresponded roughly to those of minima of barometric pressure and *vice versa* in the average semi-diurnal variation of pressure.

In that paper it was pointed out that certain related phenomena suggested that the diurnal variation in the rainfall at fronts is controlled primarily, (a) in the case of cold fronts by the thermo-dynamical working of insolation and radiation on the more or less clear sector in advance of the front, and (b) in the case of warm fronts by the corresponding effects of insolation and radiation on the cloudy warm air above the upsliding surface. It was considered however that diurnal land effects might play some part in the matter and that it would in any case be desirable (a) to repeat the investigation using data for outlying island stations which could be regarded as approximating to undisturbed Atlantic conditions, and (b) to see whether and how depressions change in regard to their precipitation in crossing the British Isles.

In consequence of a recommendation made by the Advisory Committee for the Meteorological Office, Edinburgh in 1928, autographic recording instruments were installed at Butt of Lewis in 1929 and a hyetograph was added to the equipment at Tiree. Data having thus become available for stations at Tiree and Butt of Lewis, the further investigation became possible; the results are outlined below. Funds for the erection of the instruments and for clerical assistance were provided from the Research Vote of the Meteorological Office. The assistance afforded in this way and the interest of the Committee are gratefully acknowledged, as well as the occasional assistance of members of the Edinburgh Office staff.

The period covered is again one of three years, but this time it extends from October 1929 to September 1932. The data are classified as described in *Geophysical Memoirs* No. 53 and the diurnal variations have been examined for warm front and cold front rainfall separately. The amounts, the frequencies of occurrence and the intensities have all been considered in the present case and this procedure has been applied also to the Aberdeen, Eskdalemuir and Kew data of the period 1922–4.

It should be pointed out that in the study of the precipation of the years 1929–32 at Butt of Lewis and Tiree the autographic records of wind, pressure and temperature have been used to a large extent to supplement the indications of the synoptic charts as to the position of fronts. The autographic records are particularly required in dealing with the stations on the Atlantic seaboard, because with the charts alone one would frequently be uncertain as to conditions at the boundary between the well-charted mainland regions and the sparsely represented sea areas.

* The numbers in brackets refer to the bibliography on p. 18.

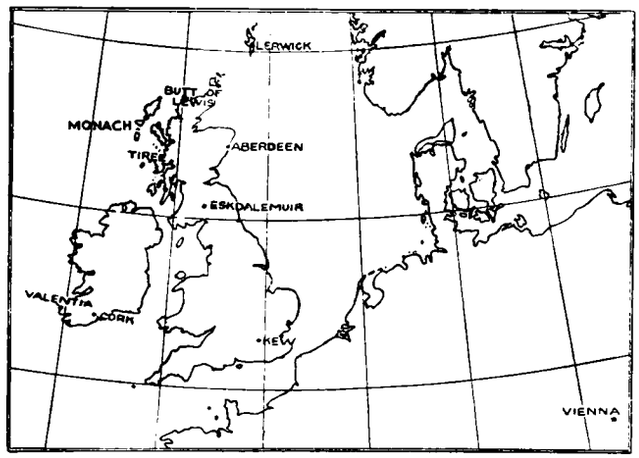


FIG. 1.—MAP SHOWING STATIONS MENTIONED IN THE MEMOIR.

Actually, however, the experience has raised the question as to whether even on land areas the frontal analysis of a synoptic chart can be carried out at all satisfactorily, with synoptic reports at six hour intervals, without the use of at least a few continuous autographic records. In different European countries, using the same synoptic information, different positions apparently are sometimes deduced for fronts; further, in using autographic records, one finds cases where fronts, fairly obvious on autographic records, have not been marked on the synoptic charts. A common condition is that with a large depression in the far north, the northern part of the country is affected very definitely by numerous secondaries. These scarcely show on the isobaric charts, but they do show on autographic records at, for example, Butt of Lewis, and then can sometimes be traced across a good part of the country. It is most probable that they affect the weather of a considerable part of the country and can sometimes explain cases of cloud, precipitation, thunder, etc. which are not apparently related to any front on the charts as drawn from the synoptic reports at fixed hours.

§ 2—DIURNAL VARIATION OF RAINFALL

Considering first the amounts of rain, the diurnal variations found for Tiree and Butt of Lewis are of the same nature as those found for the mainland stations in the paper mentioned above, that is, the warm front rainfall has a maximum during the early morning hours and a minimum in the early afternoon or near the middle of the day, whilst the cold front rainfall reaches its maximum in the late afternoon and generally has a minimum in the forenoon. The data are set out in Table I.

TABLE I—AMOUNTS OF RAIN FALLING
(OCTOBER 1929—

			1	2	3	4	5	6	7	8	9
Butt of Lewis	Summer	Warm Front ..	21·7	30·9	35·9	28·3	37·5	36·7	42·1	30·9	16·2
		Cold Front ..	10·7	12·9	15·8	12·8	14·5	15·6	20·7	11·3	12·4
		Warm Sector ..	1·1	1·0	0·4	0·6	0·9	1·1	0·2	—	0·2
		All Rainfall ..	36·4	48·3	55·9	45·8	54·2	54·3	64·6	43·0	31·4
	Winter	Warm Front ..	34·7	37·7	38·2	44·7	41·8	55·2	50·9	50·2	35·7
		Cold Front ..	38·8	31·8	35·8	37·1	31·0	38·7	22·5	30·8	21·9
		Warm Sector ..	1·4	4·0	3·1	4·5	2·1	5·8	3·7	2·6	3·2
		All Rainfall ..	90·7	83·7	86·2	100·4	81·7	106·7	83·6	89·8	70·6
Tiree	Summer	Warm Front ..	58·8	51·0	61·1	55·1	50·3	46·2	38·6	26·4	31·6
		Cold Front ..	13·3	8·4	8·2	9·7	17·6	8·5	12·9	13·4	11·4
		Warm Sector ..	2·3	1·1	1·4	1·2	1·2	1·1	1·1	1·0	0·2
		All Rainfall ..	79·0	61·7	72·9	69·1	72·0	60·1	53·8	41·6	43·6
	Winter	Warm Front ..	49·8	48·3	47·2	50·8	41·5	37·9	28·8	35·2	36·8
		Cold Front ..	25·3	20·7	26·8	30·0	30·3	18·4	18·8	19·1	17·0
		Warm Sector ..	1·2	7·5	4·5	5·5	4·7	6·6	4·7	8·2	9·0
		All Rainfall ..	79·9	80·7	83·6	91·3	79·0	67·2	56·1	66·6	72·1

As data for five stations have now been examined in this way a comparison will be of interest. To make this comparison we have taken from each curve*, in its smoothed form, the range of the diurnal variation and expressed this range as a percentage of the mean amount of rainfall per hour throughout the whole day. Table II below gives the results.

In Fig. 2 and Table III are given the mean diurnal variations at warm and cold fronts respectively as derived from the data of these five stations taken together.

TABLE II—RANGE OF THE SMOOTHED DIURNAL VARIATION EXPRESSED AS A PERCENTAGE OF THE MEAN HOURLY RAINFALL

	Summer. %	Winter. %
Warm Fronts—		
Butt of Lewis	102	74
Tiree	87	84
Eskdalemuir	56	79
Aberdeen	75	45
Kew	106	89
Mean ..	85	74
Cold Fronts—		
Butt of Lewis	125	67
Tiree	125	93
Eskdalemuir	204	168
Aberdeen	68	(71)
Kew	100	160
Mean ..	124	112

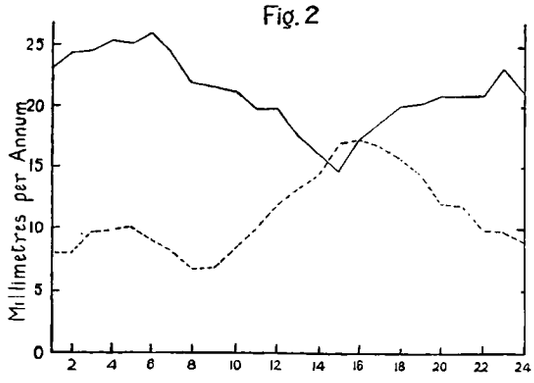
AT EACH HOUR OF THE DAY (MM.).
SEPTEMBER 1932)

10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Day
19·6	24·4	30·8	21·8	15·5	12·3	12·5	13·5	18·1	19·9	23·3	24·6	32·2	21·2	31·7	601·6
12·4	14·8	26·0	39·8	18·7	21·6	18·2	29·1	23·3	26·5	16·5	13·5	8·2	8·0	13·1	416·4
2·7	2·3	2·9	3·3	0·9	1·4	0·9	1·9	4·2	4·6	3·0	1·1	1·2	2·3	1·8	40·0
37·2	46·3	62·5	67·0	36·4	37·4	35·4	46·3	46·8	53·4	45·2	42·5	47·3	36·9	53·0	1127·5
43·4	35·1	34·4	38·8	31·1	22·8	24·0	30·0	35·5	29·3	26·4	32·6	31·9	34·4	29·0	867·8
37·2	38·4	33·7	29·6	40·8	49·5	54·3	48·0	42·3	42·4	29·7	37·3	44·6	44·3	40·9	901·4
4·7	9·3	10·8	4·2	9·4	5·0	6·9	7·7	4·4	3·9	3·3	1·5	2·4	3·8	6·2	113·9
95·8	91·4	94·5	84·8	88·8	84·0	91·1	90·1	85·3	80·8	63·9	79·2	86·5	90·4	90·9	2090·9
36·3	34·1	25·3	24·0	26·7	24·5	32·0	26·6	23·6	26·2	30·1	31·2	26·8	42·2	55·0	829·0
12·6	9·6	14·9	18·1	19·8	17·9	23·7	24·8	33·2	16·0	13·5	13·8	11·1	9·4	7·9	349·7
0·2	0·2	0·4	0·4	0·2	0·8	1·3	0·7	1·5	0·9	1·0	1·3	2·3	1·0	1·2	24·0
50·1	45·7	41·8	43·4	48·8	44·2	57·6	52·7	58·6	43·5	45·0	47·3	41·1	55·1	68·8	1297·5
33·8	37·5	31·0	31·2	22·2	17·8	19·8	31·4	28·8	30·1	34·1	35·9	32·7	34·4	32·0	883·7
22·9	32·1	33·0	31·8	32·5	38·3	45·2	56·1	33·7	47·6	48·9	44·6	32·6	30·5	25·9	762·1
7·9	4·0	5·9	5·9	8·7	6·1	3·5	2·4	2·6	2·5	2·7	5·0	1·0	0·7	1·1	111·9
70·6	81·0	75·3	75·3	67·8	70·4	72·8	97·6	75·6	84·9	88·2	91·5	72·0	70·7	70·9	1841·1

* The graphs for individual stations are not reproduced in this memoir.

From Table II we see that in both warm front and cold front rain the diurnal variations are slightly increased in summer as compared with winter. Kew cold fronts are an exception. In fact in the case of cold fronts there is definite indication of a reversal of behaviour in passing across the country from west to east. We will return to this point later. On the average, cold front rain has a greater diurnal variation than warm front i.e. a range of 118 per cent. as against 80 per cent. of the mean ; the maximum effect, if we may accept Eskdalemuir as representative, seems to be just near the west coast.

Taking all stations together the effects shown in Fig. 2 seem to be that daytime solar radiation tends, (a) to prevent or reduce warm front rain so that the minimum effect usually comes in the afternoon and the maximum in the early morning, and



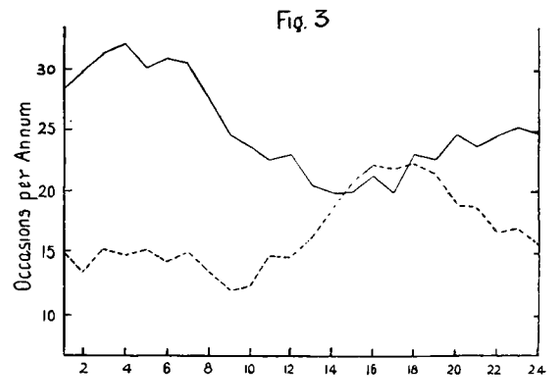
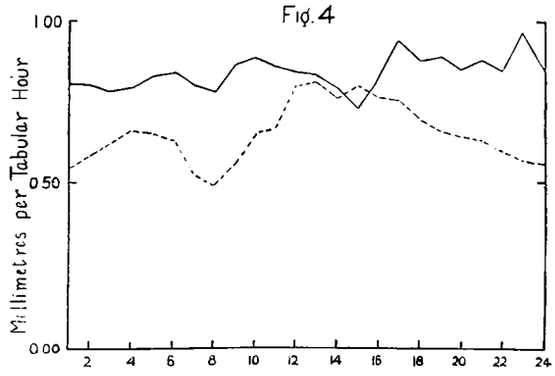


Fig. 2 — Average Amount of Warm Front and Cold Front Rainfall falling at each hour of the day.

Fig. 3 — Average Frequency.

Fig. 4 — Average Intensity measured as Amount falling per occasion per Tabular Hour.

Warm Front ——— Cold Front - - -



DIURNAL VARIATION OF RAINFALL—MEANS FROM FIVE STATIONS EACH FOR THREE YEARS.

TABLE III—DIURNAL
(Totals for 5 stations

		1	2	3	4	5	6	7	8	9	10	11
Warm Front	Summer..	172	169	181	172	171	171	168	129	127	140	140
	Winter ..	173	196	187	208	205	218	200	198	196	177	155
	Year ..	345	365	368	380	376	389	368	327	323	317	295
Cold Front	Summer..	44	48	57	52	65	57	60	37	44	44	50
	Winter ..	76	69	86	93	83	76	60	62	57	80	99
	Year ..	120	117	143	146	148	133	120	99	101	124	148

(b) to encourage or increase cold front rain, so that the maximum cold front rain comes in the afternoon and usually the late afternoon, whilst the minimum is in the forenoon. In more or less clear and also stable equatorial air the variation of temperature at ground level will be greater than in the polar air at ground level. Thus by day (and especially over land) the isobaric surfaces in the upper air will be more greatly bulged upward in the warm sector than in the cold air. This in turn induces movements which assist occlusion. At night the opposite effect will occur, i.e. the warm sector will tend to broaden and the depression will appear to become more active. Thus by night the tendency is for the two fronts to separate more widely and tend to two V-shaped depressions, whereas by day the tendency is towards occlusion of the warm sector. Probably the summer tendency over the British Isles is in general towards occlusion. Further, the point where this occluding process is most rapid will tend by reason of the convective eviction of warm air to be the locus of a new centre of low pressure and cyclonic circulation.

§ 3—INTENSITY AND FREQUENCY OF OCCURRENCE

The question which naturally arises is whether the diurnal variations found in the amount of rainfall arise from (a) a greater frequency of occurrence of passage of warm and cold fronts at the hours affected, or (b) more frequent occurrence of rain at these hours when fronts are near or (c) greater intensity of rain at these hours. The first possibility may be examined by compiling a record of the times at which fronts pass a particular station. This was done for Tiree for a period of over two years and the table below gives the results.

Table IV shows a very definite semi-diurnal variation in the frequency of passage of fronts, and a much more obvious one than for other minima of pressure. Also, the diurnal term is such as to lead to a maximum for warm fronts in the early morning and for cold fronts in the late afternoon.

As to the second and third possibilities, the data for frequency of occurrence of rainfall are set out in Table V. whilst mean values for intensity are set out in Table VI. The data for intensity have been derived by dividing the totals of the tabulated hourly amounts by the number of occasions on which rain fell within the hour. The measure of intensity arrived at in this way is not the same thing as the mean rate of fall during the time when rain is actually falling, because rain will not have been continuous throughout every tabular hour. The mean intensity derived as described above will therefore always give a figure lower than the mean rate of rainfall as ordinarily understood and as used in a later part of this paper.

VARIATION OF RAINFALL

in whole millimetres.)

12	13	14	15	16	17	18	19	20	21	22	23	24	Day
137	117	112	109	146	133	155	162	173	146	156	169	168	3621
158	143	129	110	113	149	147	142	140	166	157	178	145	3993
295	260	241	219	259	282	302	304	313	312	313	347	313	7614
80	102	98	114	100	96	110	93	66	71	50	43	38	1619
97	96	116	140	157	154	123	121	115	106	97	102	94	2358
177	198	214	253	257	249	233	214	181	177	147	145	132	3977

TABLE IV—NUMBER OF PASSAGES OF DISCONTINUITIES AT VARIOUS HOURS (TIREE) JULY 1930—OCTOBER 1932

Hour	1–3	4–6	7–9	10–12	13–15	16–18	19–21	22–24	All day.
Warm Fronts	6	12	2	7	4	5	10	2	48
Cold Fronts	6	10	8	7	6	15	6	4	62
Other Minima of Pressure	8	6	6	7	3	4	5	6	45
All cases	20	28	16	21	13	24	21	12	155

There is no very significant difference between amount and frequency curves at Tiree and Butt of Lewis. This presumably means that the intensity of the rainfall measured as described above is not much affected and that the diurnal variations in amount of warm front and cold front rainfall at these stations arise mainly from the greater frequency with which the warm or cold front rain falls at

TABLE V—FREQUENCY OF OCCURRENCE OF RAIN AT EACH

		1	2	3	4	5	6	7	8	9
		Butt of Lewis								
Warm Front	Summer	38	51	53	55	54	62	46	49	24
	Winter	57	52	65	62	54	58	58	59	42
Cold Front	Summer	20	24	30	28	28	36	34	26	17
	Winter	58	52	57	54	49	49	51	54	36
		Tiree								
Warm Front	Summer	71	78	76	71	68	68	59	46	50
	Winter	59	64	70	66	61	57	52	46	46
Cold Front	Summer	27	25	23	25	34	32	35	28.	23
	Winter	50	42	48	50	50	32	39	31	33
		Aberdeen								
Warm Front	Summer	21	21	23	28	30	28	32	24	22
	Winter	34	32	28	29	31	27	34	36	36
Cold Front	Summer	9	9	9	11	11	16	15	13	14
	Winter	11	7	11	10	11	10	12	10	16
		Eskdalemuir								
Warm Front	Summer	50	57	55	57	53	56	61	48	46
	Winter	57	60	63	68	63	65	67	61	60
Cold Front	Summer	18	12	15	12	16	12	11	13	13
	Winter	15	16	18	16	14	12	16	12	16
		Kew								
Warm Front	Summer	16	16	16	16	13	17	17	15	16
	Winter	22	17	23	29	27	28	34	34	29
Cold Front	Summer	8	7	7	8	8	7	9	9	8
	Winter	8	8	11	7	7	7	3	6	5
										Totals for
Warm Front	Summer	196	223	223	227	218	231	215	182	158
	Winter	229	225	249	254	236	235	245	236	213
	Year	425	448	472	481	454	466	460	418	371
Cold Front	Summer	82	77	84	84	97	103	104	89	75
	Winter	142	125	145	137	131	110	121	113	106
	Year	224	202	229	221	228	213	225	202	181

certain times of the day. There is, however, on the whole, a slight tendency for the intensity to follow the same sort of diurnal variation as the frequency. At Eskdalemuir, however (warm front days, winter), we find that the total amount of rain falling in the early morning hours is about double that falling just after midday, whilst the frequency of occurrence is increased only by rather more than half. Thus here the variation in intensity is in the same direction as that in frequency and rather more obvious in magnitude. The intensity figures for individual stations are, however, found to vary somewhat irregularly and it is probably best to base consideration of this question mainly on the mean values for the five stations; these are given in Table VI. The mean values of frequency and intensity are shown diagrammatically in Figs. 3 and 4. A comparison of Figs. 2, 3 and 4 confirms that the diurnal variations in the amount of rainfall in the case of warm fronts are in the main due to variation in frequency of occurrence. This may arise in part from warm front rain lasting over a greater number of hours when the fronts pass at a favourable time. In the case of cold fronts the intensity also contributes, having itself an interesting semi-diurnal variation with a secondary maximum

HOUR OF THE DAY. (PERIOD OCTOBER 1929—SEPTEMBER 1932)

10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
						Butt of Lewis								
33	34	32	33	33	28	23	22	23	31	34	37	37	33	39
46	46	42	45	44	40	42	39	38	38	43	39	47	45	49
20	21	27	32	30	34	37	39	45	49	39	35	30	24	26
54	59	43	56	55	64	72	68	72	75	55	62	57	70	57
						Tiree								
48	42	35	29	34	44	44	38	39	41	52	51	54	64	61
45	41	38	37	36	26	31	30	39	39	40	36	38	43	40
21	22	26	22	28	32	37	39	40	30	32	38	31	31	24
30	45	46	42	49	54	55	60	54	48	63	59	53	56	58
						Aberdeen								
14	20	32	15	19	25	26	25	32	30	29	25	27	28	31
29	32	27	27	23	18	23	20	26	26	30	29	28	23	26
14	13	10	15	17	14	17	17	20	22	17	15	13	14	15
10	11	13	15	17	21	21	16	21	24	18	18	13	13	15
						Eskdalemuir								
43	37	46	40	40	37	43	43	51	49	49	45	46	52	43
52	41	49	41	41	47	48	44	54	43	50	43	48	49	48
14	19	24	27	31	28	28	27	28	18	15	17	12	10	12
15	14	19	21	22	29	32	31	34	32	23	21	20	17	16
						Kew								
14	18	21	19	14	18	22	20	23	20	19	22	19	20	17
31	29	24	22	16	18	17	17	20	23	23	29	24	22	17
5	8	6	9	14	16	15	12	12	10	10	8	9	6	6
4	8	10	14	17	19	18	19	18	14	13	12	13	13	8
five Stations														
152	151	166	136	140	152	158	148	168	171	183	180	183	197	191
203	189	180	172	160	149	161	150	177	169	186	176	185	182	180
355	340	346	308	300	301	319	298	345	340	369	356	368	379	371
74	83	89	95	120	124	134	134	135	129	113	113	95	85	83
113	137	130	148	160	187	198	194	199	193	172	172	156	169	154
187	220	219	243	280	311	332	328	334	322	285	283	251	254	237

TABLE VI—DIURNAL VARIATION

(Values derived by dividing the total hourly amounts recorded at five stations

		1	2	3	4	5	6	7	8	9
Warm Front	Summer	·88	·76	·81	·76	·78	·74	·78	·71	·80
	Winter	·75	·87	·75	·82	·87	·93	·82	·84	·92
	Year	·81	·81	·78	·79	·83	·84	·80	·78	·87
Cold Front	Summer	·54	·62	·68	·62	·67	·55	·58	·42	·59
	Winter	·53	·55	·59	·68	·63	·69	·50	·55	·54
	Year	·54	·58	·62	·66	·65	·63	·53	·49	·56

in the early morning hours. This appears in both summer and winter, but is more marked in summer.

It will be noticed that both the amount and the intensity curves (Figs. 2 and 4) for warm front rain show a hump at 23h. It scarcely appears in the frequency curves of Fig. 3. This hump comes from the winter half of the year; it might be legitimate to dismiss it as a chance irregularity of the statistics, but it appears in the data of every single station, in Tiree and Butt of Lewis data for the period 1929–32 and in Aberdeen, Eskdalemuir and Kew data for the period 1922–4.

§ 4—TOTAL AMOUNTS OF RAINFALL AT FRONTS

As mentioned in the previous paper, a very large proportion of the rain which falls in the outer islands can be readily ascribed to warm or cold fronts. Table VII indicates that of the balance a certain amount can at once be allotted to the warm

TABLE VII—AMOUNTS OF RAIN FALLING IN VARIOUS CONDITIONS (MM.)

	Butt of Lewis				Tiree			
	Summer		Winter		Summer		Winter	
	Amount	Percentage of total fall	Amount	Percentage of total fall	Amount	Percentage of total fall	Amount	Percentage of total fall
Warm Front ..	601·6	53	867·8	42	883·7	68	829·0	45
Cold Front ..	416·4	37	901·4	43	349·7	27	762·1	41
Warm Sector..	40·0	3	113·9	5	24·0	2	111·9	6
Other Rain ..	69·5	7	207·8	10	40·1	3	138·1	8
Total	1127·5		2090·9		1297·5		1841·1	

OF INTENSITY OF RAINFALL

by the number of hours in which rain occurred.)

10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
·92	·93	·83	·86	·80	·72	·93	·90	·92	·95	·95	·81	·85	·86	·88
·87	·82	·88	·83	·81	·74	·70	·99	·83	·84	·75	·95	·85	·98	·81
·89	·87	·85	·84	·80	·73	·81	·95	·88	·89	·85	·88	·85	·92	·84
·61	·60	·90	1·07	·82	·92	·75	·72	·82	·72	·58	·63	·53	·51	·46
·71	·72	·75	·65	·73	·75	·80	·80	·62	·63	·67	·62	·62	·60	·61
·66	·67	·81	·82	·77	·81	·77	·76	·70	·66	·64	·63	·59	·57	·56

sectors of depressions. The amount that is left over, unallocated, averages only 7 per cent. and of even that small amount it is probable that on re-examination an appreciable proportion could be allocated to some part of a depression. In Table VIII some results are gathered together indicating the proportion of rain, in different areas, that is not readily ascribable to fronts. This includes rain in apparently more or less homogeneous polar or equatorial currents and rain in the warm sectors of depressions. Taking the summer figures we see that in the outer islands rain of this sort is only 10 per cent. of the total; in west Scotland it rises to 29 per cent., in east Scotland to 40 per cent. and in south-east England to 51 per cent. In winter the differences are less striking, ranging from 16 per cent. to 40 per cent.

We thus reach certain important conclusions. The forecasting of rain by strict interpretation of pressure maps (other things such as the available network

TABLE VIII—RELATIVE PROPORTIONS OF RAIN AT FRONTS AND IN OTHER CIRCUMSTANCES

	At warm fronts	At cold fronts	At Fronts	In other circum-stances	Percentages of total rain not obviously associated with a discontinuity	
					Summer	Winter
Individual Stations:						
Butt of Lewis (1929–32) ..	..	..	88	12	..	..
Tiree (1929–32)	..	..	90	10	..	..
Monach Islands (1922–4) ..	..	..	83	17	..	..
Eskdalemuir (1922–4) ..	..	..	69	31	..	..
Aberdeen (1922–4) ..	..	..	60	40	..	..
Kew (1922–4)	..	..	57	43	..	..
District values:						
Outer Islands	49	38	87	13	10	16
West Scotland	53	16	69	31	29	32
East Scotland	44	16	60	40	40	40
South-east England ..	39	18	57	43	51	35

of reporting stations being supposed equal), or even from local observation of pressure and sky changes, might be expected to meet with a considerable measure of success in the outer islands and at sea. On the mainland however something like 30 per cent. to 50 per cent. of the total rainfall would apparently be regarded as casual if considered strictly in relation to the pressure maps. It comprises rain from more or less homogeneous polar or equatorial currents considerably removed from any obvious discontinuity, rain in the warm sector and rain of purely orographic origin (arising from topographical causes but not directly or at least obviously associated with any depression). On the mainland therefore there are important development effects which tend to obscure the importance of the rôle played by the fronts of the depressions. At the same time, as mentioned in the introductory remarks, the development effects could perhaps in many cases be related to discontinuities observable and traceable with the assistance of autographic records.

In these differences we see probably the explanation of the importance which in Norway—a maritime country lying close to the main tracks of primary depressions —is attributed to frontal analysis of the weather map and of the relatively smaller importance which is ascribed to that kind of analysis in England and in central and southern European countries.

Going into greater detail in so far as the British Isles are concerned, it appears that as regards all Scotland (with the exception perhaps of the part lying to eastward of the Grampians), all Ireland and all the western side of England, the successful forecasting of rain turns largely on accurate frontal analysis coupled with an estimate of the result of the diurnal effects. As regards the eastern, midland and south-eastern parts of England the problem, especially in summer, is largely of a different sort. Again, different from either, we can probably regard the part of east Scotland lying to eastward of the Grampians and the north-eastern part of England. According to the writer's personal experience the lowland part of Scotland, including Edinburgh, Glasgow and the populous part of the country, appears most commonly to come under the western regime ; that is, its forecasting problem is most often the maritime one.

There is another way of establishing the physical reality of the distinction between maritime and mainland forecasting. The depressions affecting the British Isles are undoubtedly more intense and frequent in winter than in summer. If other things were equal we should therefore expect much more rain and much higher average wind speeds in winter months than in summer months. But statistics show at a glance that this type of seasonal variation, though characteristic of the western maritime stations, is practically obliterated in the south-eastern part of the country. This is quite well known, but the question of taking it into account in forecasting is another matter.

Broadly we may perhaps sum up the situation by saying that the primary disturbances—the large scale eddies—come from the general circulation over the Atlantic and that the weather of a large part of the British Isles—the more maritime part—is directly controlled by them ; but that the weather of the south-eastern and parts of the eastern side of the country is largely under the influence of developed eddies of a secondary order.

§ 5—RATES OF RAINFALL

A consideration of the rates of rainfall in different parts of the country and in various conditions reveals some points of interest. Some relevant data were tabulated and examined as described below. Some mean values for other stations have also been extracted from the tables of rates of rainfall published annually in *British Rainfall*. The values of rate of rainfall are here obtained by dividing the total fall for the month or year by the total duration of rain.

The data for annual variation are shown in Table IX.

TABLE IX—MEAN RATES OF RAINFALL (MM. PER HOUR)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1929–32	Butt of Lewis	1·55	1·38	1·05	1·44	1·50	1·43	1·38	1·33	1·42	1·52	1·43	1·60	1·42
	Tiree ..	1·33	0·91	0·97	1·20	1·16	1·24	1·19	1·43	1·26	1·51	1·42	1·29	1·24
1925–31	Lerwick ..	1·10	1·07	0·95	1·13	1·20	1·27	1·27	1·40	1·25	1·33	1·23	1·00	1·17
	Aberdeen ..	1·07	0·90	0·87	1·00	1·17	1·23	1·30	1·33	1·25	1·27	1·13	1·00	1·13
	Eskdalemuir	1·30	1·03	0·90	1·07	1·25	1·50	1·50	1·65	1·25	1·47	1·40	1·15	1·33
	Kew.. ..	0·95	1·15	0·93	1·13	1·37	1·73	2·13	2·03	1·60	1·37	1·37	1·03	1·40
	Cork.. ..	1·37	1·25	1·20	1·37	1·43	1·30	1·60	1·67	1·47	1·47	1·90	1·33	1·45
	Valentia ..	1·73	1·43	1·55	1·47	1·55	1·45	1·43	1·97	1·55	1·70	1·93	1·57	1·63
1919–31	Valentia ..	1·67	1·60	1·60	1·50	1·53	1·40	1·57	1·93	1·65	1·73	1·87	1·70	1·70

The annual variation in rate of rainfall is found to be closely similar at the Scottish stations, Lerwick, Aberdeen, Eskdalemuir and Tiree. Butt of Lewis does not show much annual variation, but, in common with the majority of other stations, has a conspicuous minimum in March. The mean derived from these five stations is shown graphically in Fig. 5. There is a conspicuous principal minimum about March and a secondary minimum in September; a principal maximum in August and a secondary one in October. At Kew the range of the annual variation is doubled; the principal maximum comes rather earlier in summer (July) and there is a slight secondary maximum in autumn. In south-west Ireland (Valentia and Cork) on the other hand there is less annual variation, in fact, there is a generally high rate of rainfall, but there are still rises in August and late autumn. The mean rate at Valentia seems high, but this feature is supported by statistics over a longer period 1919–31 which have been added to Table IX.

Fig. 5 — Scottish Stations

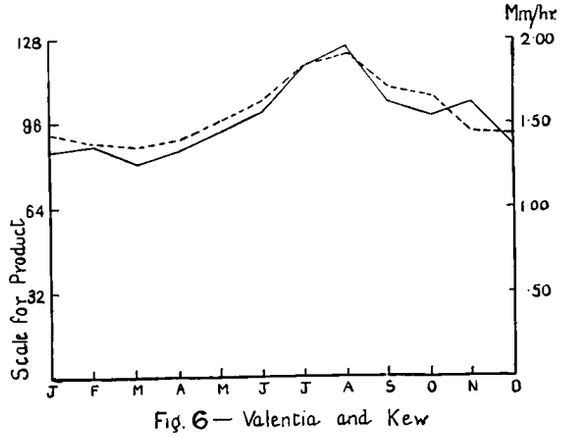


Fig. 6 — Valentia and Kew

ANNUAL VARIATION OF THE MEAN RATE OF RAINFALL (FULL LINE) AND OF THE PRODUCT "WIND SPEED BY VAPOUR PRESSURE" (BROKEN LINE)

The general trend of the annual variation in Scotland agrees closely with the annual variation of the product "wind speed by vapour pressure." In order to eliminate as far as possible the influence of land surface effects (frictional or convectional) on wind speed, the mean speed included in this formula was the mean of Butt of Lewis, Lerwick, Tiree and Bell Rock for the years that were available up to 1932; the vapour pressure was the mean of Eskdalemuir and Aberdeen taken from hourly values for the years 1925–31 inclusive. The annual curve for the resulting product is shown in Fig. 5. Though there are minor departures in individual

months, the annual variations agree very closely in phase and amplitude. The mean relationship between the three quantities is given by the formula :

$$r = Wq/120$$

where r = rate of rainfall in mm. per hour.

W = wind speed in m.p.h.

and q = vapour pressure in mb.

Assuming that the greater part of the rain is produced by upsliding currents we may deduce an average value for the angle of slope. Corresponding to r=2 mm./hr. we have $q = 10{\cdot}3$ mb. at ground level and the vertical velocity w requires to be about 400 ft. per hour. The corresponding $W = 14{\cdot}3$ m.p.h., so that the average upward slope of the air movement is roughly 1 : 200. This result assumes that all the water which is condensed out of the rising air falls to the ground as rain. That is probably never the case ; the rain will most frequently fall through a current of different origin from that in which it originated, and a good deal of the rain may in this way be evaporated again. Thus the slope of the discontinuity in the average case undoubtedly requires to be greater than the value derived above. Possibly 1 : 150 or even 1 : 100 would be nearer the usual average value over Scotland.

Rates up to 5 or 7 mm./hr. occur in warm fronts at Tiree where there can be little, if any, orographic effect. These rates could be accounted for by wind speeds of the order of 35–50 m.p.h. and slopes of the order just mentioned, or equally by lower wind speeds and more steeply sloping surfaces of discontinuity.

Again, to represent the mean rate of rainfall in the southern part of the country we take a mean between Valentia and Kew and make curves corresponding to those of Fig. 5. In this case the mean vapour pressures and wind speeds used are also simply the means of Valentia and Kew. Fig. 6 shows the result. Again the annual variations are in general agreement, the formula indicated in this case being

$$r = Wq/64$$

The decrease in the denominator of the fraction from 120 to 64 is unlikely to arise solely from the use of a W which under-represents the effective mean wind speed, because the mean annual value of the W for Valentia and Kew is 9·9, whilst for the Scottish stations it was 17·3. It therefore seems unlikely that an effective mean wind speed higher than perhaps 14 m.p.h. would be applicable. This would change the denominator from 64 to about 90. The remaining difference between this factor and that found for the Scottish stations is perhaps to be accounted for by a steeper average upsliding angle of the rain-bearing currents or perhaps from a greater proportion of rainfall of instability type caused by the greater convectional effects of the broader land area in the southern part of the country.

It has to be remembered further that, particularly from about November to May, there is a considerable difference between the mean rates of rainfall at Valentia and Kew. If we treat the data of these two stations separately, then the mean rates of rainfall at Valentia in each month from November to May are very definitely above what would be indicated by the products of wind speed and vapour pressure, whilst in the same period at Kew the mean rates of rainfall are correspondingly low. The agreement between the curves in Fig. 6 may therefore be the accidental result of circumstances which work in opposite directions at the west and east sides of the country.

More exact information about instantaneous " rates of rainfall " in individual cases is obtainable from the Jardi rate of rainfall recorders which have been in use at some observatories for a few years. It is found that the rate of rainfall even at warm fronts varies a good deal from one time to another, though generally in a gradual fashion. The Jardi records of the years 1932 and 1933 at Eskdalemuir Observatory were tabulated in the following manner. For each case of warm front rainfall the predominant rate of rainfall and the extreme rate were tabulated. If there was no predominant rate the mean rate was estimated. The mean of the

predominant rates was found to be 2 mm./hr. and the mean of the extreme rates was 7 mm./hr. The highest rates noted during the period, at any warm front were a mode of 4 mm./hr. and a momentary extreme of 18 mm./hr. on the night of July 30–31, 1933. In the Eskdalemuir records there is no evidence of any characteristic variation of rate of rainfall as a warm front passes.

In order to see whether there was any characteristic variation in the rate of rainfall during the passage of a warm front in a place free from topographical effects, all the cases were extracted from the Tiree records where the rain, even if only intermittent, had been spread over 10 hours or more, and the mean hourly amounts for the first hour, second hour, etc. were worked out. For Tiree 70 cases were available and the resulting means were as under :

Hour	1	2	3	4	5	6	7	8	9	10
Mean amount for the tabular hour (mm.)	0·38	0·72	0·82	0·74	0·65	0·61	0·63	0·56	0·58	0·60

The first hour is the first tabular hour in which rain occurred ; if the average time of commencement be taken as half way through this hour, then the amount for the first hour should be doubled to give a measure of rate comparable with the other figures, i.e. it becomes 0·76. It is then seen that though the rain on the average rises to a maximum in the third hour, the variation of rate is very gradual, the maximum rate being only 22 per cent above the mean (0·67), and the lowest rate—about the eighth hour—being only 16 per cent below the mean. When the data are divided into two groups the maximum rates come in the third and fourth hours respectively. The Jardi records at Eskdalemuir give some support to the idea that the heaviest rain is frequently two or three hours after the start, but, as already mentioned, it cannot be said that there is any characteristic behaviour.

The Eskdalemuir Jardi records were examined also in regard to occluded fronts and cold fronts. In these cases, and particularly at occluded fronts, there was enormously greater variation in the extreme rates of rainfall, and some of the summer extremes reached values of the order of 80 mm./hr. For occluded fronts the mean of the mean rates was again 2 mm./hr. ; the mean of the extreme rates was however 18 mm./hr. For cold fronts the mean of the means was again 2 mm./hr. and the mean of the extremes was 14 mm./hr. A mean rate for cold fronts however is in general a mean between zero rate and excursions up to 10, 20 or 30 mm./hr. In what follows in regard to comparative rates of rainfall at warm and cold fronts this point must particularly be kept in mind. Nevertheless it was thought desirable to inquire what changes were introduced in the passage of fronts from the Outer Islands across the British Isles.

To examine this point the days of the period 1929–32 were classified into groups termed respectively *S*, *Q* and *SQ*, the first being days on which the rain was entirely or mainly of warm front type, the second, days on which it was entirely or mainly of cold front type and the third, days on which appreciable proportions of both cold front and warm front rain had occurred. The amounts and durations of rainfall for these groups of days for Butt of Lewis and Tiree were tabulated and then summarized in order to arrive at the actual mean rates of fall in different conditions. The same process was completed with the rainfall records of Aberdeen, Eskdalemuir, Kew and Valentia for the years 1922–4. A point of some difficulty in connexion with rainfall at cold fronts has already been mentioned. This is somewhat emphasized when hyetograph records are used, because in these cases it is possible that the recorded durations of heavy showers are longer than the actual durations and that the computed rates are to this extent rendered lower than the true mean rate. It has already been shown above that with warm front rain a fairly constant or gradually varying rate of fall covers most of the period ; there is thus every reason to suppose that the computed rates for warm front rainfall,

as obtained from the hyetograms, represent very closely the actual mean rates. Also, over the whole country, including the extreme western stations, warm fronts are responsible for a greater total amount of rain than cold fronts.

The comparative results are set out in Table X. We may first mention three

TABLE X—MEAN RATES OF RAINFALL (MM./HR.) ON VARIOUS TYPES OF DAYS

	Mean of all rainfall	Summer			Winter		
		S	*Q*	*SQ*	*S*	*Q*	*SQ*
Eskdalemuir (1922–4) ..	1·20	1·26	1·28	1·31	1·18	1·05	1·42
Kew (,,) ..	1·27	1·20	1·39	1·67	1·10	1·10	1·41
Aberdeen (,,) ..	1·28	1·27	1·57	2·05	1·06	1·08	1·27
Valentia (,,) ..	1·84	2·10	1·79	2·62	2·12	1·91	1·91
Butt of Lewis (1929–32) ..	1·42	1·31	1·55	1·41	1·17	1·71	1·55
Tiree (,,) ..	1·24	1·21	1·23	1·04	1·21	1·48	1·41

Mean Values

	Summer			Winter		
	S	*Q*	*SQ*	*S*	*Q*	*SQ*
Butt of Lewis and Tiree	1·26	1·34	1·23	1·19	1·59	1·48
Eskdalemuir and Valentia	1·68	1·53	1·97	1·65	1·48	1·67
Aberdeen and Kew	1·23	1·48	1·86	1·08	1·09	1·34

Q/*S* Ratios

	Summer	Winter
Extreme west	106	134
West coast	91	90
East coast	120	101

points of interest though they perhaps do not bear on questions of travel. The first is that the notably high rates at Valentia appear here again. The next point for comment is that at the west coast (Eskdalemuir and Valentia) the rate of rainfall at cold fronts is less, both in summer and in winter, than at warm fronts. Here the warm front rate is high from a topographical effect; one cannot eliminate such an effect and therefore little, if anything, as to behaviour of depressions can be deduced from these stations. The third point which may be noted is that at the mainland stations generally, both east and west, the rate of rainfall for days characterized by both warm and cold fronts is greater than the mean rate on days with cold fronts alone or warm fronts alone. Many of the days of the *SQ* class are days with warm front rain in the early morning and cold fronts in the late afternoons. In these cases the warm sector passes in the middle of the day and it seems that diurnal influences can then operate in such manner as to cause the strongest developments. But in many cases also occluded fronts fall in this class and these, as already seen from the Jardi records, are characterized frequently by high rates of rainfall.

To get an idea now of the nature of the development, if any, with travel as depressions pass across the British Isles, the results have been arranged in three groups, extreme west (Butt of Lewis and Tiree), west coast (Eskdalemuir and

Valentia) and east coast (Aberdeen and Kew). In the extreme west in summer and in the east in winter there is no marked difference between the mean rates of rainfall at warm and cold fronts. In the extreme west in winter and in the east in summer the rate of fall is markedly higher at the cold fronts than at the warm fronts. There is thus an important seasonal reversal of effects in the east as compared with the extreme west, arising in both cases apparently from a magnification of the cold front rainfall; this is doubtless associated with instability and it will be recalled that the frequency of thunderstorms (which are instability phenomena) shows a similar reversal in seasonal behaviour as between the extreme west and the east sides of the country.

§ 6—COMPARISON WITH CONTINENTAL CONDITIONS

In two recently published papers M. Kofler (2) (with some references to earlier work of the present writer) discusses the distribution of rain at Vienna in relation to its daily period and the diurnal variation of barometric pressure in relation to temperature change. Considering the distance of Vienna from the western European seaboard and its highly continental climate, it is of interest to compare the results of Kofler's investigation with those outlined in the present paper. Taking the data for the year as a whole he finds maxima both in frequency and amount of rainfall for the hours ending 7h. and 20h. respectively, the earlier maximum being more marked in the frequency figures and the latter more marked in the amount figures. He shows also that, on the whole, rainfall is above the mean for the day during the two periods of rising barometric pressure and discusses the relation of the periods of enhanced barometric pressure to the periods of temperature change. The change from winter to summer in rainfall conditions at Vienna consists largely in a development of the frequency and amount of afternoon rainfall and in almost the suppression of the early morning maximum; actually, in this season, the late afternoon hours yield twice as much rain as the early morning hours.

He favours a classification of rainfall on the following lines:—

(1) Intrinsically convectional rainfall, arising, by reason of increased temperature in the lower layers, especially in the warmer part of the year.

(2) Rainfall associated with cooling, occurring mainly when temperature is falling and especially in the colder parts of the year.

(3) Rainfall arising from upward air movement of dynamical origin, corresponding to the semi-diurnal pressure variation, at all times of the year, and possibly associated with turbulence checks to the general air flow.

Broadly this view agrees with the results outlined in the present paper. The first factor just mentioned favours the development of cold front rainfall, the second factor increases warm front rainfall, whilst the third factor probably applies generally.

It is of interest, further, to compare the details of the mean diurnal variation of rainfall at Vienna, a highly continental station, with those of Tiree and Butt of Lewis as representing a close approach to purely maritime conditions. In the mean diurnal variation (of all rainfall) at these maritime stations it is possible to identify three features as probably corresponding to features in the mean diurnal variation as shown at Vienna. These are the early morning maximum at 4h. G.M.T., the principal minimum at 9h. and the afternoon maximum at 17h. G.M.T.; the corresponding features at Vienna occur at 7h., 12h. and 20h. mid-European time respectively, i.e. 6h., 11h. and 19h. G.M.T. Thus even considered in universal time there is a net lag of two hours at Vienna. Actually the longitude difference between Tiree or Butt of Lewis and Vienna is about $1\frac{1}{2}$ hours so that, considered in each case with reference to local time, the principal features of the diurnal variation at Vienna each come $3\frac{1}{2}$ hours later in the day than they do at Tiree and Butt of Lewis. There is similar evidence, at least in the case of the afternoon

maximum of cold front rain, of a definite lag at Kew as compared with Eskdalemuir or Tiree and Butt of Lewis. Thus we cannot regard the principal features of the diurnal variation of rainfall as being altogether independent of geographical conditions. Either there are continentality effects which retard the principal turning points or there are superposed effects which travel from the west. It is scarcely possible that the retardation could be explained by actual travel of individual diurnally developed effects over distances of the order of that between the western British seaboard and Vienna, but it is possible that in favourable circumstances or places such effects could frequently start and could travel for west-east distances of the order of one or two hundred miles before dying out ; and in this way inland continental stations could have relatively delayed maxima of rainfall.

§ 7—SUMMARY

Characteristic diurnal variations are found in the amounts of warm front and cold front rainfall, at extreme western stations as well as at mainland stations. It is found that the higher amounts of rain at given times of the day arise mainly from greater frequency of occurrence at these times. In general the main effects everywhere are greater frequency of warm front rain during the night and early morning hours, greater frequency of cold front rain in the afternoon and chiefly the late afternoon ; there is also greater intensity of cold front rain in the early afternoon and a secondary maximum in the early morning.

A brief examination is made of the mean amounts and rates of rainfall in different places, seasons and meteorological conditions. The same kind of result comes out when we consider total amounts of rain as when we consider rates of fall. From Table I or Table VII it can be seen that at the extreme western stations, Butt of Lewis and Tiree, the cold front rain in summer is roughly only half as much in total amount as the warm front rain, whilst in winter the cold fronts give roughly the same total as the warm fronts. At the eastern stations on the other hand it is only in summer that the cold fronts give a total approximately equal to the warm fronts ; in winter they give a total of about 70 per cent. of the warm front total. In regard to rates of rainfall, the rate at cold fronts rises in winter at the western stations and rises in summer at the eastern stations, whilst the rate at warm fronts shows less seasonal change.

These results indicate very considerable changes in the precipitation of depressions as they pass across the British Isles. Any statement as to average amounts of rain at different places must be made with a good deal of qualification as to the limitations of the value of averages, but the following summary may be taken as a general guide to the behaviour at west and east coast places as compared with the outer islands.

Warm Front Rain. In summer the average result is that, as compared with Butt of Lewis and Tiree, the warm front rain of a depression is increased at Eskdalemuir or Valentia by some 30 per cent. through orographic effects and is diminished by various effects at Aberdeen by 35 per cent. and at Kew by over 50 per cent. In winter the increase at Eskdalemuir is about 30 per cent., at Valentia about 70 per cent., the decrease at Aberdeen is about 40 per cent. and at Kew about 50 per cent.

Cold Fronts. In summer Eskdalemuir and Aberdeen get about the same amount of cold front rain as the outer islands. Valentia and Kew get about 50 per cent. of that amount. In winter Eskdalemuir and Valentia get little more than half of the outer islands cold front rain, whilst Aberdeen and Kew get only about a quarter.

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Wt.3603/2810 6.36 625 CT&CoLtd Gp330: S.O. Code No. 40-27-69